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Launch Vehicle Performance for Bipropellant Propulsion Using Atomic Propellants With Oxygen

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LAUNCH VEHICLE PERFORMANCE FOR BIPROPELLANT PROPULSION USING ATOMIC PROPELLANTS WITH OXYGEN

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ABSTRACT

Atomic propellants for bipropellant launch vehicles using atomic boron, carbon, and hydrogen were analyzed. The gross liftoff weights (GLOW) and dry masses of the vehicles were estimated, and the "best" design points for atomic propellants were identified. Engine performance was estimated for a wide range of oxidizer to fuel (O/F) ratios, atom loadings in the solid hydrogen particles, and amounts of helium carrier fluid. Rocket vehicle GLOW was minimized by operating at an O/F ratio of 1.0 to 3.0 for the atomic boron and carbon cases. For the atomic hydrogen cases, a minimum GLOW occurred when using the fuel as a monopropellant (O/F = 0.0). The atomic vehicle dry masses are also presented, and these data exhibit minimum values at the same or similar O/F ratios as those for the vehicle GLOW. A technology assessment of atomic propellants has shown that atomic boron and carbon rocket analyses are considered to be much more near term options than the atomic hydrogen rockets. The technology for storing atomic boron and carbon has shown significant progress, while atomic hydrogen is not able to be stored at the high densities needed for effective propulsion. The GLOW and dry mass data can be used to estimate the cost of future vehicles and their atomic propellant production facilities. The lower the propellant's mass, the lower the overall investment for the specially manufactured atomic propellants.

NOMENCLATURE

A	Fixed mass scaling parameter (kg)
Al	Aluminum
B	Boron
B	Propellant dependent mass scaling parameter (kg/kg M_p)
C	Carbon
GLOW	Gross Lift Off Weight
H	Atomic hydrogen
He	Helium
H_2	Molecular Hydrogen
I_{sp}	Specific impulse (s)
M_p	Propellant mass (kg)
NLS	National Launch System
O/F	Oxidizer to Fuel ratio, or Mixture ratio
O_2	Oxygen
wt%	Weight Percent

INTRODUCTION

Atomic propellants have great potential for increasing rocket specific impulse, and reducing the cost for access to space. With atomic propellants, the rocket specific impulse (I_{sp}) can be increases many hundreds of seconds over oxygen/hydrogen rockets, thereby opening new and previously impossible opportunities in space access. Figure 1 depicts the gross liftoff weight (GLOW) reductions that are possible with atomic boron propellants (Ref. 1). While the potential for these propellants is great, they are not a near term solution for space transportation. Much research is needed to store the atoms successfully at high atom weight percent (wt%) values for rocket and airbreathing propulsion. This paper describes the selection of the "best" design points for atomic fueled rockets, and the issues that must be addressed during their system design.

PAYOFFS FOR ATOMIC PROPELLANTS

Using high energy density materials (HEDM) as propellants, the cost of space access can be reduced for future airbreathing and rocket-powered space vehicles. Increasing the payload mass per flight, and/or reducing the complexity of vehicle operations enables the cost reductions. The ways to increase vehicle payload performance with advanced fuels are reducing the gross lift off weight (GLOW), reducing the dry weight, and reducing vehicle size due to increased fuel density, or increased specific impulse, or both.

The costs of launching to Earth orbit are a major challenge to reducing in-space transportation costs. If the payload to orbit per flight were increased, the number of launches to effect missions is reduced. This reduction in launches and the attendant cost reductions are particularly important for missions to the outer Solar System, or any high-energy space mission. The effective mission travel time is also reduced, in that the reduced number of launches reduces the time for on-orbit assembly of large space vehicles. These time reduction analyses were conducted for human Mars missions (Ref. 2), and the results were impressive. The time to deliver payload to orbit, and ultimately to Mars, were reduced by many years using metallized gelled propellants, or $O_2/H_2/Al$, with increases in I_{sp} of 10 seconds. New HEDM propellants can provide near term incremental benefits in increased specific impulse (I_{sp}) that will save years of assembly costs for large space missions. Future far-term atomic HEDM propellants may deliver 100's of seconds of increased Isp over O_2/H_2 propulsion. This performance increase can translate into more compact space vehicles, with GLOW values that are up to 80 percent less than that of current launch vehicle designs. These GLOW reductions can be translated into hundreds of percents increases (264 to 360% with atomic hydrogen) in payload mass delivered to orbit. As an example, a 96,000-kg payload can be increased to over 170,000 kg with 50-wt% boron, and to over 475,000 kg with a 50-wt% atomic hydrogen rocket. These payload increase cases can allow one heavy lift launch vehicle to deliver a complete human interplanetary space vehicle to orbit. This launch capability would save billions of dollars and many years of time by eliminating on-orbit assembly. When speed is essential, atomic propellants can ultimately open up the Solar System, from the ground up.

Using atomic propellants in aeronautical and space vehicles has many challenges, and their solutions will spring from both basic physics and engineering (Ref. 3-28). A current vision of the vehicle propellant design includes using solid particles of molecular hydrogen to store the atoms. The particles are then stored in liquid helium at 3-4 K temperatures. The liquid helium will also aid the flow of the atom-laden hydrogen particles. The challenges for these propellants include high rates of atom formation, stable storage of the atoms, and storage of the atoms in solid cryogenic hydrogen particles. To make an effective feed system, the vehicle will have to have ground support equipment to form millions of the solid cryogenic particles, and provide reliable flow of these particles from the propellant tank to the combustion or recombination chamber (Ref. 1). In addition, the temperature of the particles must remain at 3 to 4 K until they are to be used in the rocket combustion chamber, and be protected from the high heat fluxes typical of high-energy rocket engines.

ATOMIC ROCKET VEHICLES

Atomic rocket vehicles were designed using tankage and vehicle mass estimating codes (Ref. 1) and rocket performance analyses using the CET program (Ref. 29). Helium addition of 10-, 20-, and 40-wt% was computed to simulate the addition of a carrier fluid to aid the flow of solid hydrogen particles from the propellant tanks to the rocket engine (Ref. 1). Other assumptions regarding the selection of the atom wt% loadings, and the fuel densities for the B, C, and H with varying helium addition wt% values are discussed in Ref. 1. The general vehicle sizing assumptions are also provided in Ref. 1, and specific sizing assumptions for the higher O/F bipropellant cases are discussed in the succeeding sections.

Rocket Engine Performance

Rocket performance estimates are provided in Figures 2 through 8. The atom wt% values were selected based on the results of Ref. 1. The boron level of 22-wt% B and the carbon level 24-wt% C represent reasonable extrapolations of what will be feasible with atomic storage in solid hydrogen. The 50-wt% B and 50-wt% C represent design points were where the atomic vehicles' GLOW is comparable to or significantly reduced over the O_2/H_2 cases (Ref. 1). All of the atomic hydrogen cases were selected based on analyses that showed potential for GLOW reductions (Ref. 1). Currently, the best storage density of atomic H is much lower than 10-wt% H, and therefore much research is needed to demonstrate these storage wt% levels. Current storage capabilities for atomic hydrogen are near 0.1-wt%, and have no possibility of providing a propulsion system gain in GLOW or engine I_{sp}. The atomic hydrogen cases are presented to illustrate what could be possible if breakthroughs in propellant technology were made. Though many of these rocket analyses represent future hopes for atomic propellants, the analyses show the place to select the best atomic propellant loadings for the "best" vehicle design with the lowest GLOW and lowest dry mass. These analyses also show what the possibilities are for payload increases for the rocket propellants.

The sensitivity of the I_{sp} to helium addition of 10-, 20-, and 40-wt% helium was also computed. In the overall view, the Isp of the rocket engines was greatly reduced by the addition of helium at the low (0.0) O/F ratio. At higher O/F ratios, the higher density oxygen replaces a fraction of the less-dense fuel. By using oxygen, the overall vehicle volume and GLOW are reduced. The GLOW can be significantly reduced because lighter tankage is needed to contain the fuel and oxidizer. The lower engine I_{sp}, along with higher oxidizer density, leads to a more mass efficient vehicle than the monopropellant vehicle. This bodes well for the higher O/F ratio engine operation, and vehicle design, especially for the lower atom wt% levels.

In Ref. 1, the rocket engine performance of the atomic engines was presented, and the effects of helium addition on the I_{sp} were shown to be small for the high atom storage, 50-wt% cases. In many cases, and even with lower atom wt% values, the operation of the rocket engine at higher O/F ratios (between 2.0 and 4.0) showed little reduction in engine I_{sp} due to the effect of helium addition. This effect is important for delivering a low GLOW, and having a successful particle flow system. Previous analyses (Ref. 1) implied that, for monopropellant operation, the higher helium wt% levels would never be beneficial for atomic rockets. Analyses for bipropellant operation has shown that in many cases, a very high 40-wt% helium level may be used, and have a relatively small effect on increasing the GLOW.

Boron: The atomic B engine I_{sp} values were estimated for a 22- and 50-wt% atom cases. For the 22-wt% B engine, the maximum I_{sp} value is 518.9 seconds at an O/F ratio of 0.5 (00-wt% He). Adding the 40-wt% He to the 22-wt% B (at an O/F = 0.5) reduced the I_{sp} to 449 seconds. With the 50-wt% case (00-wt% He), the engine I_{sp} is 651 seconds (O/F = 0.0), and the corresponding value with 40-wt% He is 522 seconds.

The engine performance with atomic boron with 40-wt% helium addition is very low at the low O/F ratios. Using the higher O/F ratios, the engine performance was found to be much less sensitive to helium addition. Figures 2 and 3 show that at the O/F ratios of 2 to 4, the effect of helium addition is relatively small, and these data were used later to find the “best” design point for the atomic rocket vehicles. If there is a small effect of the helium addition on the engine I_{sp}, this fact can be used to ease the design challenges of the feed system. With a larger helium wt%, there is a better chance to make the solid particle feed system successful.

At a 50-wt% B loading (and 00-wt% He), the maximal I_{sp} is 651.2 seconds, at an O/F ratio of 0.0. At the 40-wt% He level, the 50-wt% B engine I_{sp} is 522.3 seconds. This large disparity in the I_{sp} values leads to large differences in vehicle GLOW, and implies that the higher O/F ratios will be more important in reducing vehicle GLOW, especially if higher wt% of helium are required.

Carbon: The engine I_{sp} data for the carbon cases is depicted in Figures 4 and 5. For the 24-wt% C engine, the maximum I_{sp} value is 512.5 seconds at an O/F ratio of 0.0 (00-wt% helium). Using a 40-wt% helium addition with 24-wt% C, the I_{sp} drops to 402.8 seconds. With the 50-wt% C cases (with 00-wt% helium), the maximum I_{sp} is 696.4 seconds. For the 50-wt% C with the added 40-wt% helium, the I_{sp} drops to 570.7 seconds.

As with the boron cases, the atomic carbon engine showed lower performance at the lower O/F ratios when operating at the high helium wt% values. The monopropellant cases showed the greatest sensitivity to helium addition, and this low I_{sp} will dramatically increase the vehicle GLOW. Operating at the higher O/F ratios will assist in reducing the vehicle GLOW.

Hydrogen: The atomic hydrogen engine I_{sp} is depicted in Figures 6, 7, and 8. The engine performance was predicted for 10-, 15-, and 50-wt% H. For the 10-wt% cases, the engine I_{sp} showed great sensitivity to He addition at the low O/F cases. For this 10-wt% H engine, the maximum I_{sp} value is 611.8 seconds at an O/F ratio of 0.5 (00-wt% He). At the 15-wt% H atom loading, the maximal engine performance is 750 seconds (O/F = 0.0). With the 40-wt% helium addition, the I_{sp} drops to 588 seconds. Using the 50-wt% H (00-wt% He), the engine I_{sp} is highest at an O/F of 0.0: 1282 seconds. By adding 40-wt% He, the I_{sp} was reduced to 1046 seconds.

Vehicle Design Assumptions

In sizing the vehicles, the basic assumptions from Ref. 1 were used. All of the rocket vehicles are 2 stage designs. The payload to orbit for all the vehicles was 96,000 kg. In all cases, liquid O_2 is the oxidizer. Oxygen was selected, as it is a traditional oxidizer, and matched that of the NLS baseline vehicle. The range of O/F ratios for the atomic rockets was 0.0 to 5.0. An estimate of the tank mass was made using a 6.1 meter diameter tank, for most cases. The lowest O/F cases, 0.5 and 1.0, typically required a smaller 4.1 meter diameter tank to accommodate the smaller amount of O_2.

Mass Scaling Equations

The mass scaling equations have the general formula of (Ref. 1):

M_{dry} (kg) = A + B M_p

Summaries of the mass scaling parameters are presented in Tables I through IV. Each table presents a different O/F ratio for the propulsion system dry mass. The comparison of the monopropellant (O/F = 0.0, in Table I) and the bipropellant scaling equations (in Tables II, III, and IV) showed that the B factor is substantially reduced when designing the bipropellant propulsion systems. This reduction is the result of the higher density of the O_2. As the O/F ratio increases, the higher density oxygen is replacing some of the lower density atomic fuel. Using the higher density oxygen also reduces the engine I_{sp}, but in the overall design, the GLOW of the vehicle can be reduced over the monopropellant case. Higher propellant density results in lower vehicle dry mass, and volume over the vehicle using the lower density atomic fuel.

The monopropellant vehicle GLOW values were taken from Ref. 1. These cases were compared with the bipropellant cases, and in many instances, the bipropellant vehicles had substantially lower GLOW values. This effect was especially noted in the low atom wt% cases for B, C and H.

RESULTS

The results presented here are the GLOW of the atomic vehicles, and their dry masses. The GLOW is very important, as it shows the potential for increasing the payload capacity of rocket vehicles. The dry mass is also a historically important parameter in estimating the cost of propulsion systems (Ref. 30), and these data are also presented. Vehicle costs were not estimated in this paper, but the information is provided to assist future cost estimators in their analyses.

Gross Lift Off Weight

Boron: Figure 9 compares the GLOW of a 22-wt% B rocket for both 00-wt% He and 40-wt% for the O/F range of 0.0 to 5.0. The 22-wt% B vehicle with 00-wt% He has a minimum GLOW value at an O/F ratio of 2.0, at 2,260,000 kg, but the minimum exists broadly between the 1.0 and 3.0 O/F ratios. The monopropellant case (O/F = 0.0) was a tremendously high number, over 9,190,000 kg. For the 22-wt% cases, none of these vehicles had a lower GLOW than the baseline O_2/H_2 vehicle.

With the 22-wt% B cases with 40-wt% He, the minimum GLOW is at O/F ratio of 2.0, at 2,768,000 kg. The monopropellant case has a GLOW of 82,219,000 kg, which is quite impractical. Bipropellant operation does indeed have a powerful effect on reducing the GLOW for these lower 22-wt% cases. As with the 22-wt% cases with 00-wt% He, none of these vehicles had a lower GLOW than the baseline O_2/H_2 vehicle.

Using 50-wt% B with 00-wt% He, the vehicle GLOW is significantly lower than that for the O_2/H_2 vehicle: only 1,145,700 kg. These results are shown in Figure 10. The atomic B rocket has a lower GLOW than the O_2/H_2 vehicle until it reaches an O/F ratio of 3.0. Therefore the best operating point for the atomic B rocket is between and O/F of 0.0 and 1.0. Atomic B vehicle operating at O/F ratios less than 1.0 will have a significantly lower GLOW than an O_2/H_2 vehicle, and thus show a vehicle benefit.

When operating at 50-wt% B with 40-wt% He, the vehicle GLOW shows a minimum between and O/F ratio of 0.5 to 1.0. Both of these O/F ratios deliver atomic B vehicle GLOW values that are below the baseline O_2/H_2 vehicle's GLOW.

Carbon: Atomic C rocket GLOW with 24-wt% C and 50-wt% C is illustrated in Figures 11 and 12. An atomic C rocket with 24-wt% C and 00-wt% He has a minimum GLOW at the O/F of 3.0: 2,245,000 kg. With the 40-wt% He, the same B loading delivers a minimum GLOW of 2,815,700 kg. Both of these cases are greater in mass that the GLOW of the baseline vehicle.

At the 50-wt% C case (00-wt% He), the vehicle GLOW is a minimum at an O/F of 0.0: 975,200 kg. In all of the higher O/F cases, the GLOW was higher than the monopropellant case. At the 50-wt% C case with 40-wt% He, the minimum GLOW occurred at an O/F of 0.0: 1,735,200 kg. As with the boron cases, the 50-wt% vehicle may be able to operate at a higher O/F ratio, and still show a significant reduction in GLOW over the baseline vehicle.

Hydrogen: The atomic hydrogen GLOW values are depicted in Figure 13, 14, and 15. For the 10-wt% H cases with 00-He wt%, the GLOW values show a minimum in the O/F range of 1.0 to 2.0. Operating the atomic hydrogen vehicle at the O/F of 1.0 or 2.0 also reduced the GLOW below that of the baseline O_2/H_2 vehicle: 1,834,000 kg versus 1,891,500 for the O_2/H_2 vehicle. For the 10-wt% cases with 40-wt% He, the higher O/F ratios can significantly reduce the GLOW. The minimum GLOW occurs at in the range of O/F ratio of 2 or 3. The minimum GLOW at an O/F of 3.0 is 2,330,000 kg. Unfortunately, this GLOW is higher than the baseline O_2/H_2 vehicle. Thus the 10-wt% H vehicle seem to have only a very small benefit in reducing vehicle GLOW.

With the 15-wt% cases with 00-wt% He, the GLOW was not reduced by operating at higher O/F ratios. The minimum GLOW occurred at an O/F of 0.0 and the GLOW was 1,057,600 kg. Operating at higher O/F ratios only increased the GLOW. Though the GLOW was increased, there is the possibility of reducing the overall vehicle operating costs by using the higher O/F ratios. At the higher O/F, the amount of atomic hydrogen needed is significantly reduced, and the size of the facility or production rate for the atomic hydrogen can be reduced.

When the He addition is 40-wt% with the 15-wt% H cases, the GLOW shows a minimum value in the O/F range of 1.0 to 2.0. However, there is only a small reduction in GLOW over the baseline O_2/H_2 vehicle. At an O/F of 1.0, the atomic H GLOW is 1,842,000 versus 1,891,500 kg for the baseline vehicle. If the He addition could be reduced to 10- or 20-wt%, there is still the potential for significantly reducing the vehicle GLOW below the baseline case.

At the 50-wt% H cases with 00-wt% He, the vehicle GLOW is always greatly reduced over the O_2/H_2 baseline case. The monopropellant case (O/F = 0.0) reduced the GLOW to 411,000 kg, which is less than 22% over the O_2/H_2 vehicle GLOW. With the 50-wt% H cases, the GLOW was increased by increasing the O/F ratio. As noted earlier, operating the vehicle at a higher O/F ratio can reduce the facility size and production rate for atomic fuels. Even if the GLOW is increased over the minimum value, operating at a higher O/F ratio may significantly reduce the overall cost of the atomic vehicle.

Using the 50-wt% H case with 40-wt% He, the GLOW is still a small fraction of the O_2/H_2 baseline GLOW: only 518,000 kg. As the O/F ratio increased, the GLOW also increased. Even at the O/F of 2.0, the GLOW was still less than 50% of the baseline GLOW, with the atomic H vehicle weighing in at a mere 930,000 kg.

Vehicle Dry Masses

The atomic rocket dry masses were computed as a part of the GLOW calculations and are presented here in Figures 16 through 22. In past analyses, the space vehicle dry mass is often used as an important parameter in space mission cost estimating (Ref. 30). The dry masses are therefore presented to assist in future cost estimates for these vehicles.

Boron: The dry masses of the atomic B vehicles are presented in Figures 16 and 17. For the 22-wt% cases, the minimum dry masses occur at an O/F ratio of 2.0, and the mass is 371,500 kg. For comparison, the baseline O_2/H_2 vehicle dry mass was 197,800 kg. At the 50-wt% B case, the dry mass is almost as low as the baseline case: 210,000 kg at an O/F of 0.5.

Carbon: Figures 18 and 19 illustrate the atomic C dry mass optimizations. With atomic C (24-wt% C, 00-wt% He), the dry mass minimum occurs at the O/F ratio of 3.0 and the mass was 383,000 kg. Using 50-wt% C (00-wt% He), the minimum dry mass was 185,300 kg (O/F = 0.0). This case is where the atomic rocket has a lower dry mass that the baseline mass of 197,000 kg.

Hydrogen: Dry masses for atomic H vehicles are depicted in Figures 20, 21, and 22 for 10-, 15- and 50-wt% atom loadings of H. In the three H cases, the only design that reduced the dry mass below the baseline case was the 50-wt% H vehicle: 91,600 kg (O/F = 0.0). Even the 40-wt% He case with 50-wt% H was able to reduce the dry mass significantly below the baseline mass: 112,000 kg. Atomic hydrogen appears to be the most capable propellant for reducing both GLOW and dry mass.

OBSERVATIONS

Atomic rocket designs have much sensitivity to engine I_{sp}, and dry mass, and O/F ratio. Engine I_{sp} was shown to be an important aspect of reducing vehicle GLOW for atomic B, C, and H rockets (50-wt% cases). For these 50-wt% cases, the best atomic B, C, and H GLOW operating point seems to be the monopropellant case (O/F = 0.0). However, operating at an O/F of 1.0 or 2.0 still provides a low GLOW, and significantly reduces the total production of atomic propellant for each vehicle. Atomic propellant vehicles using bipropellant combinations can substantially reduce the mass of atomic fuel needed. This reduction can reduce the overall production facilities for the fuel, and reduce the cost of the advanced technology vehicle and propellant.

With the lower wt% atomic fuel cases, though the Isp values were relatively low for the higher O/F cases, the overall bipropellant vehicle GLOW and dry mass were greatly reduced over the B, C, and H monopropellant vehicle cases. A monopropellant atomic B vehicle had a GLOW of over 82,000,000 kg and the optimal design at an O/F of 2.0 reduced the GLOW to 2,226,000 kg, a phenomenal mass reduction.

In the GLOW analyses presented here, the effects of helium addition were also small in some cases for lower atom wt% values, especially, at the higher O/F ratios. In the boron and carbon cases, the vehicle GLOW is surprisingly insensitive to the He addition near the minimum GLOW values. The GLOW of the atomic B vehicle (22-wt% B) in Figure 9 and atomic C vehicle (24-wt% C) in Figure 11 show that there was little difference between the GLOW values for the 00-wt% He and the 40-wt% He cases. This result was unexpected and can be a powerful tool in creating a practical atomic fueled vehicle.

Once the GLOW is computed and compared to the baseline O_2/H_2 vehicle, the mass difference between the baseline and the new atomic rocket can be used to estimate the potential payload increase. These analyses were based on the assumption that the atomic rocket GLOW can be allowed to equal the baseline vehicle GLOW. With atomic boron rockets, the payload increases can be 70%, whereas if atomic hydrogen were proven feasible in some far future, the payload increase might be 360%.

The GLOW and dry mass data can be used to estimate the cost of future vehicles and their atomic propellant production facilities. The lower the propellants mass, the lower the overall investment for the specially manufactured atomic propellants.

CONCLUSIONS

Using a bipropellant oxygen/ atomic fueled vehicle very significantly reduced the GLOW of atomic rockets. All of the cases using less than 50-wt% atomic fuel loading, the vehicle GLOW showed an optimum or minimum GLOW between an O/F ratio of 1.0 and 3.0. This minimization of the GLOW is important for the lower wt% atomic loading cases, as they may be the first implementations of these very advanced rocket fuels. Monopropellant operation (O/F = 0.0) provided the lowest GLOW values for the vehicles using 50-wt% atomic fuel: B, C, or H.

In many cases, operating the atomic propellant vehicle at O/F ratios of 1-3 is very effective in reducing the atomic fuel needed and, ultimately, the fuel production costs. Using the 22-wt% B cases, the overall mass of fuel was reduced by nearly a factor of 2 percent with an O/F of 1.0. The best O/F ratio appears to be 2.0 for minimum GLOW. The overall system design, which balanced the GLOW reduction, dry mass, and fuel production needs, implies an O/F ratio between 1.0 to 3.0 was best.

A technology assessment of atomic propellants has shown that atomic boron and carbon rocket analyses are considered to be much more near term options than the atomic hydrogen rockets (Ref. 4-11, and 31). The technology for storing atomic boron and carbon has shown significant progress, while atomic hydrogen is not able to be stored at the high densities needed for effective propulsion. Future near term work should concentrate on atomic boron and atomic carbon propellants.

In the boron and carbon rocket cases, operating the vehicle at an O/F ratio of 2 to 4 showed that the rocket I_{sp} was little influenced by the addition of helium. The GLOW of the vehicle using 40-wt% He was not greatly increased over the 00-wt% cases. If there is a small effect of the helium addition on the engine I_{sp}, this fact can be used to ease the design challenges of the feed system. With a larger helium wt%, there is a better chance to make the solid particle feed system successful.

CONCLUDING REMARKS

Atomic fuels have the potential for revolutionizing aerospace vehicles. Airbreathing propulsion systems may use them to accelerate the combustion process in scramjet engines (Ref. 32). Rocket engine I_{sp} can be significantly increased, but the density of the fuel and the vehicle must be selected to make the vehicle as effective as possible. Selection of the “best” O/F ratios for the atomic rocket vehicle can reduce the GLOW very significantly, and make the vehicles of a practical size and mass. Cost estimates of future vehicles must include the very expensive atomic propellant facilities. The operation of atomic chemically-propelled rockets may be driven by operating far from the theoretical maximum I_{sp}

values, and be more controlled by the forces of economics. As our understanding of the basic physics of atomic propellants increases, the perceived costs of creating “impossible” atomic propellants will drop, and a new era of engineering, physics, and exploration will begin.

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Table I
Dry Mass Scaling Parameters for Atomic Rockets: O/F = 0.0

Atomic Boron

Wt% B	Wt% He	A	B
22	00	11,934.32	0.29681
22	40	11,934.32	0.28302
50	00	11,934.32	0.24228
50	40	11,934.32	0.25030

Atomic Carbon

Wt% C	Wt% He	A	B
24	00	11,934.32	0.29340
24	40	11,934.32	0.28097
50	00	11,934.32	0.24328
50	40	11,934.32	0.25089

Atomic Hydrogen

Wt% H	Wt% He	A	B
10	00	11,934.32	0.33966
10	40	11,934.32	0.30867
15	00	11,934.32	0.33966
15	40	11,934.32	0.30867
50	00	11,934.32	0.33966
50	40	11,934.32	0.30867

Table II
Dry Mass Scaling Parameters for Atomic Rockets: O/F = 1.0

Atomic Boron

Wt% B	Wt% He	A	B
22	00	11,516.99	0.22327
22	40	11,898.11	0.21638
50	00	11,516.99	0.19601
50	40	11,898.11	0.20002

Atomic Carbon

Wt% C	Wt% He	A	B
24	00	11,516.99	0.22157
24	40	11,898.11	0.21535
50	00	11,516.99	0.19650
50	40	11,898.11	0.20031

Atomic Hydrogen

Wt% H	Wt% He	A	B
10	00	11,898.11	0.24470
10	40	11,898.11	0.22923
15	00	11,898.11	0.24470
15	40	11,898.11	0.22923
50	00	11,898.11	0.24470
50	40	11,898.11	0.22923

Table III
Dry Mass Scaling Parameters for Atomic Rockets: O/F = 2.0

Atomic Boron

Wt% B	Wt% He	A	B
22	00	11,516.99	0.19876
22	40	11,516.99	0.19416
50	00	11,516.99	0.18058
50	40	11,516.99	0.18326

Atomic Carbon

Wt% C	Wt% He	A	B
24	00	11,516.99	0.19762
24	40	11,516.99	0.19348
50	00	11,516.99	0.18091
50	40	11,516.99	0.18345

Atomic Hydrogen

Wt% H	Wt% He	A	B
10	00	11,516.99	0.21304
10	40	11,516.99	0.20273
15	00	11,516.99	0.21304
15	40	11,516.99	0.20273
50	00	11,516.99	0.21304
50	40	11,516.99	0.20273

Table IV
Dry Mass Scaling Parameters for Atomic Rockets: O/F = 3.0

Atomic Boron

Wt% B	Wt% He	A	B
22	00	11,516.99	0.18650
22	40	11,516.99	0.18306
50	00	11,516.99	0.17287
50	40	11,516.99	0.17488

Atomic Carbon

Wt% C	Wt% He	A	B
24	00	11,516.99	0.18565
24	40	11,516.99	0.18254
50	00	11,516.99	0.17312
50	40	11,516.99	0.17502

Atomic Hydrogen

Wt% H	Wt% He	A	B
10	00	11,516.99	0.19722
10	40	11,516.99	0.18948
15	00	11,516.99	0.19722
15	40	11,516.99	0.18948
50	00	11,516.99	0.19722
50	40	11,516.99	0.18948

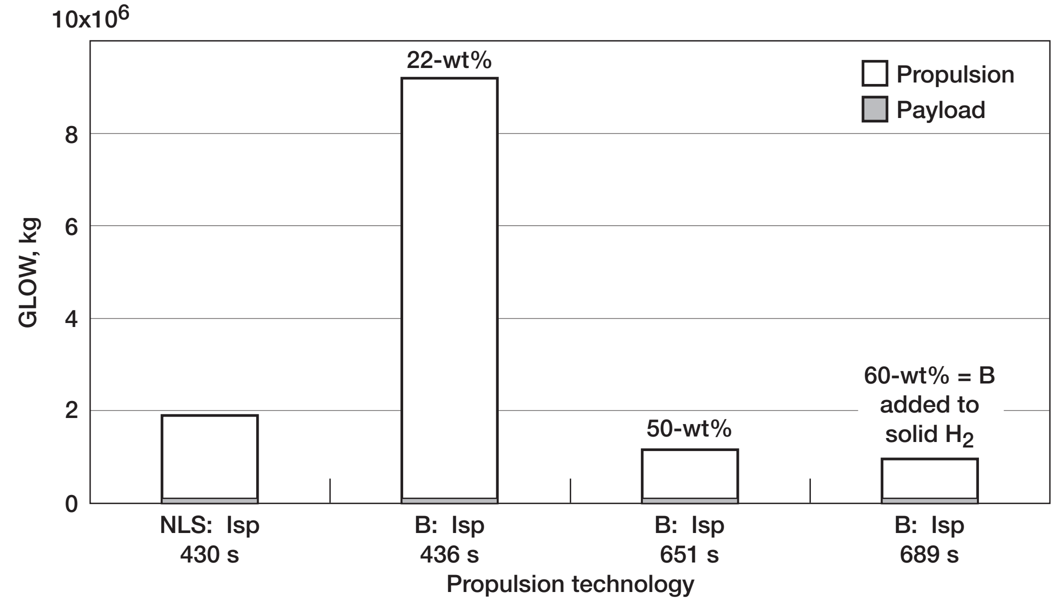

Figure 1.—Atomic boron GLOW for monopropellants: 22–, 50–, and 60–wt% B. No helium addition

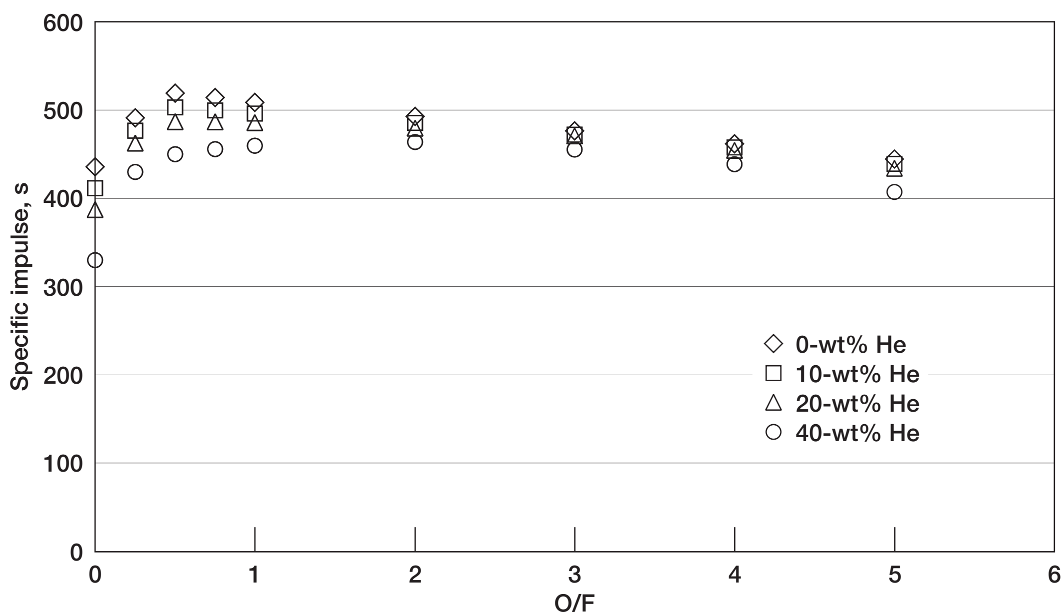

Figure 2.—Atomic boron engine performance: 22–wt% B.

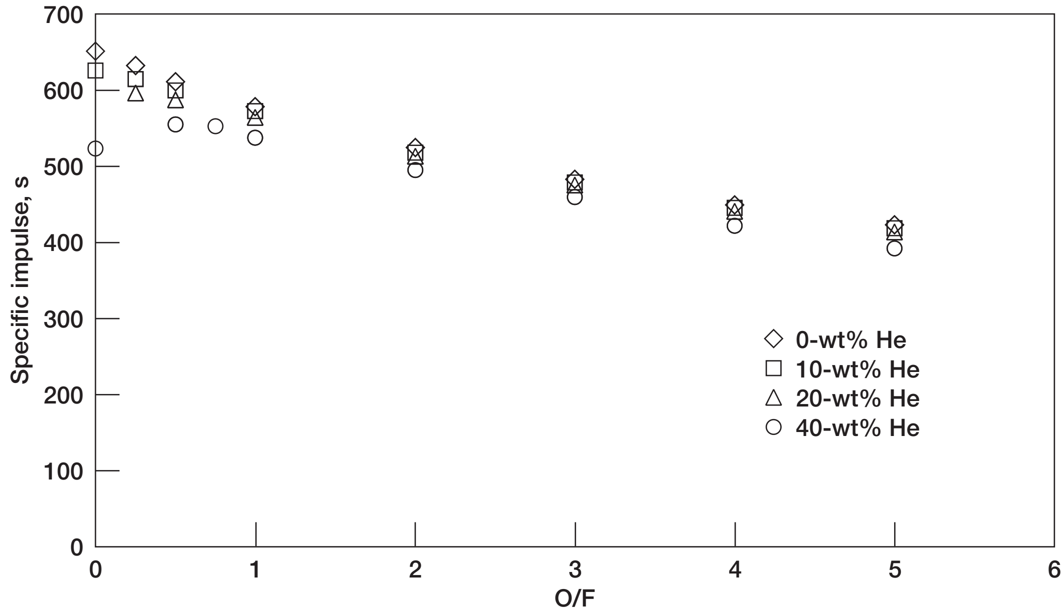

Figure 3.—Atomic boron engine performance: 50–wt% B.

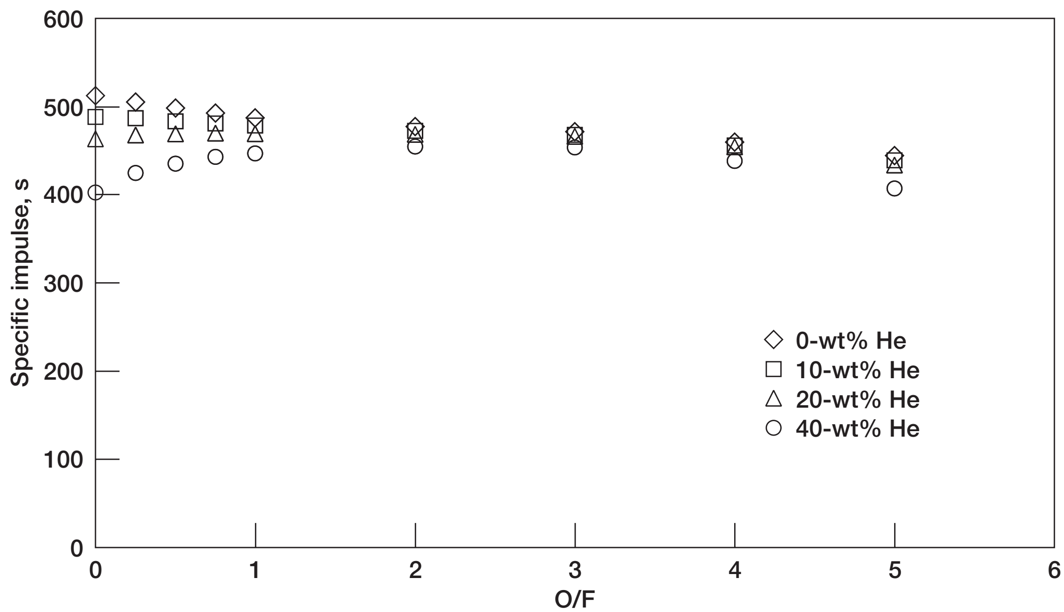

Figure 4.—Atomic carbon engine performance: 24–wt% C.

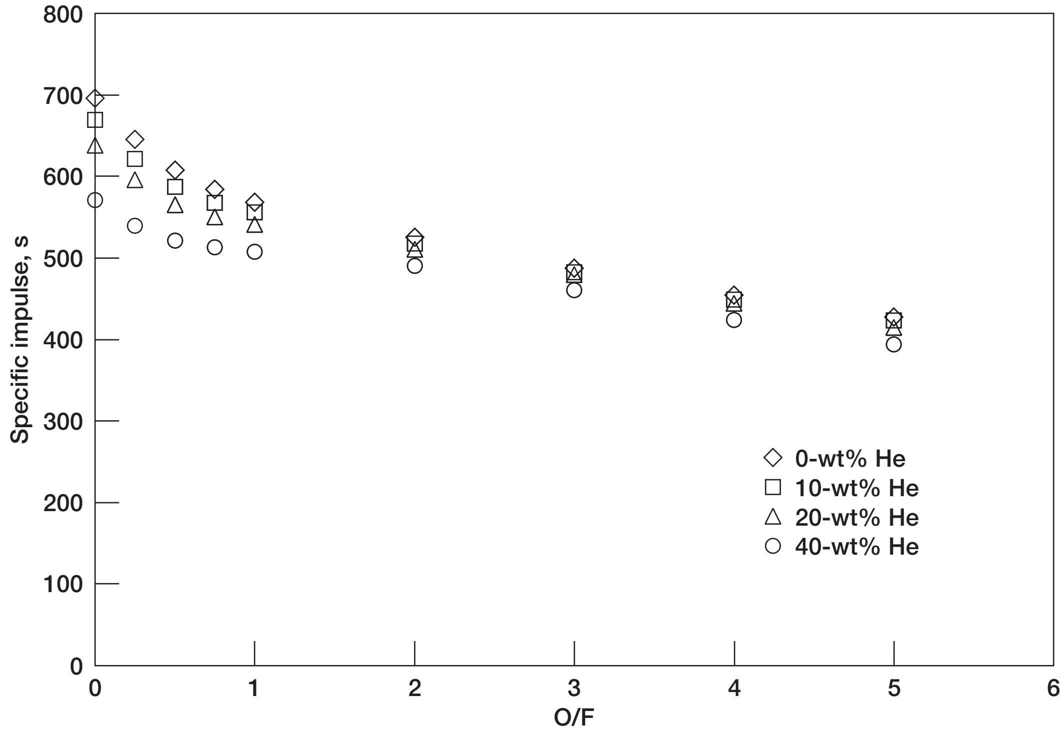

Figure 5.—Atomic carbon GLOW: 50–wt% C.

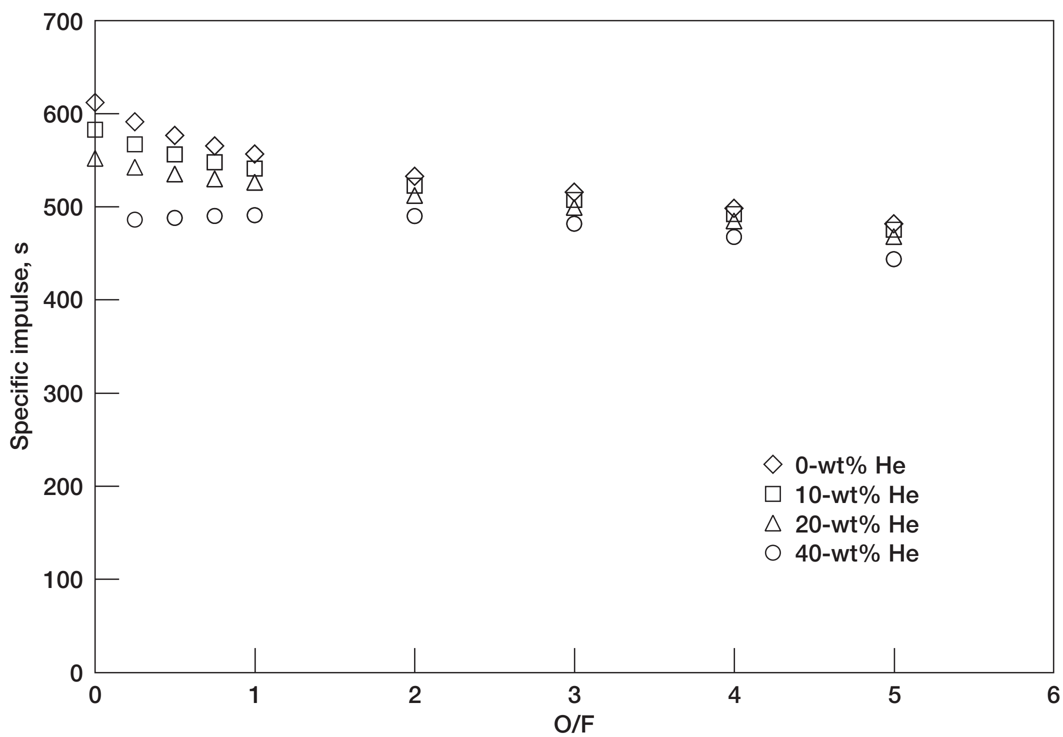

Figure 6.—Atomic hydrogen engine performance: 10–wt% H.

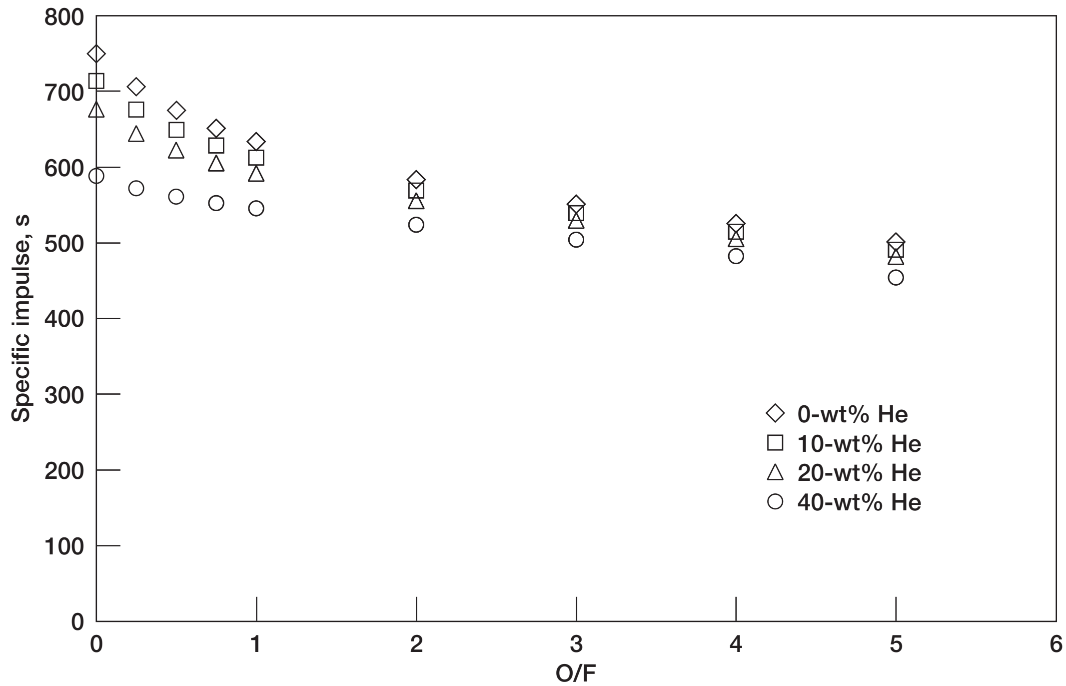

Figure 7.—Atomic hydrogen engine performance: 15–wt% H.

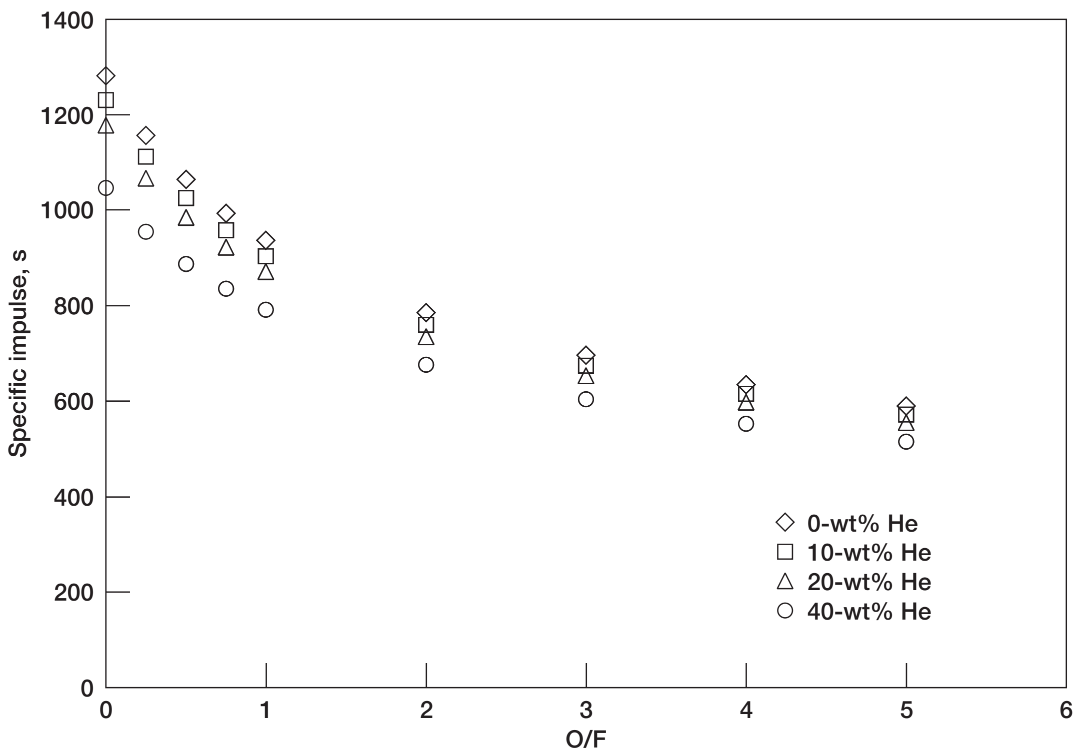

Figure 8.—Atomic hydrogen engine performance: 50–wt% H.

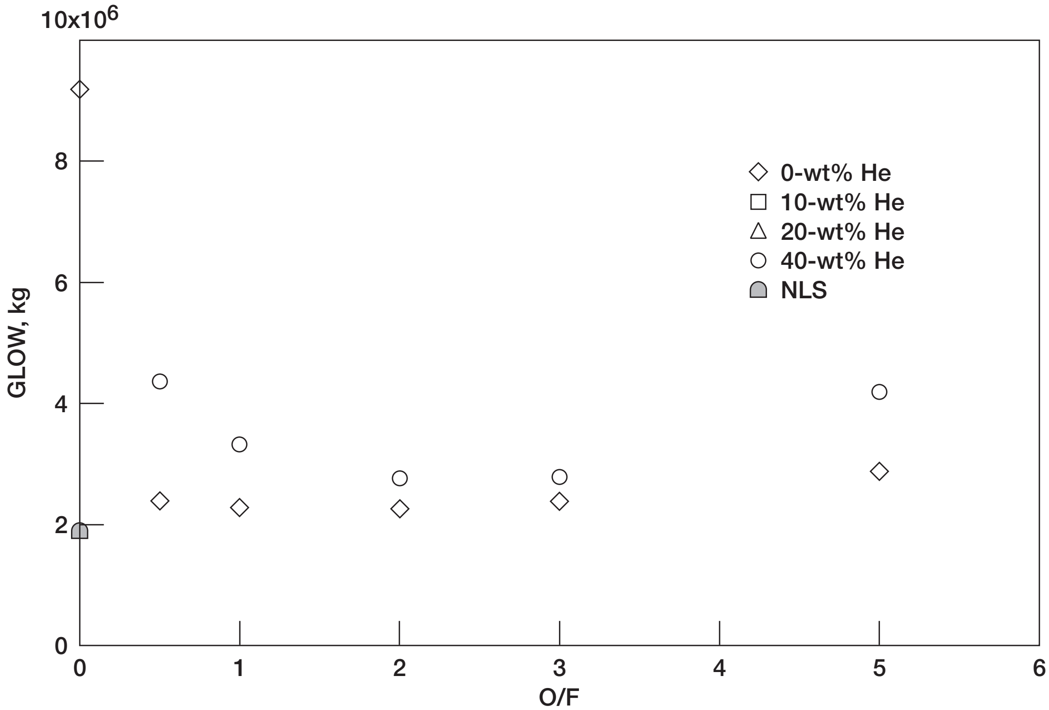

Figure 9.—Atomic boron GLOW: 22–wt% B.

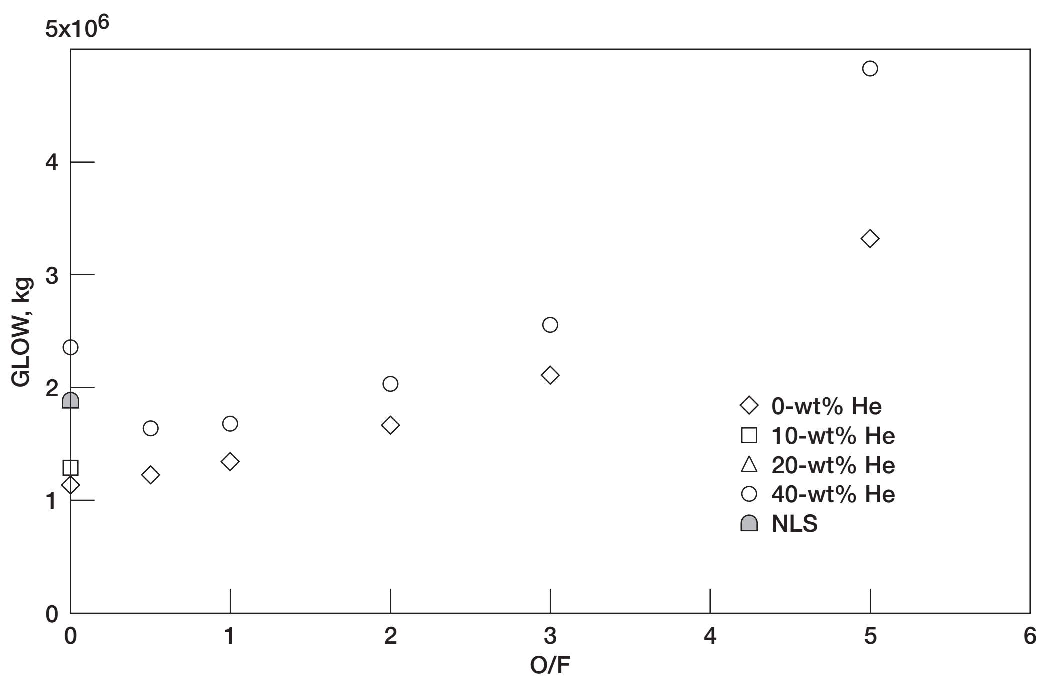

Figure 10.—Atomic boron GLOW: 50–wt% B.

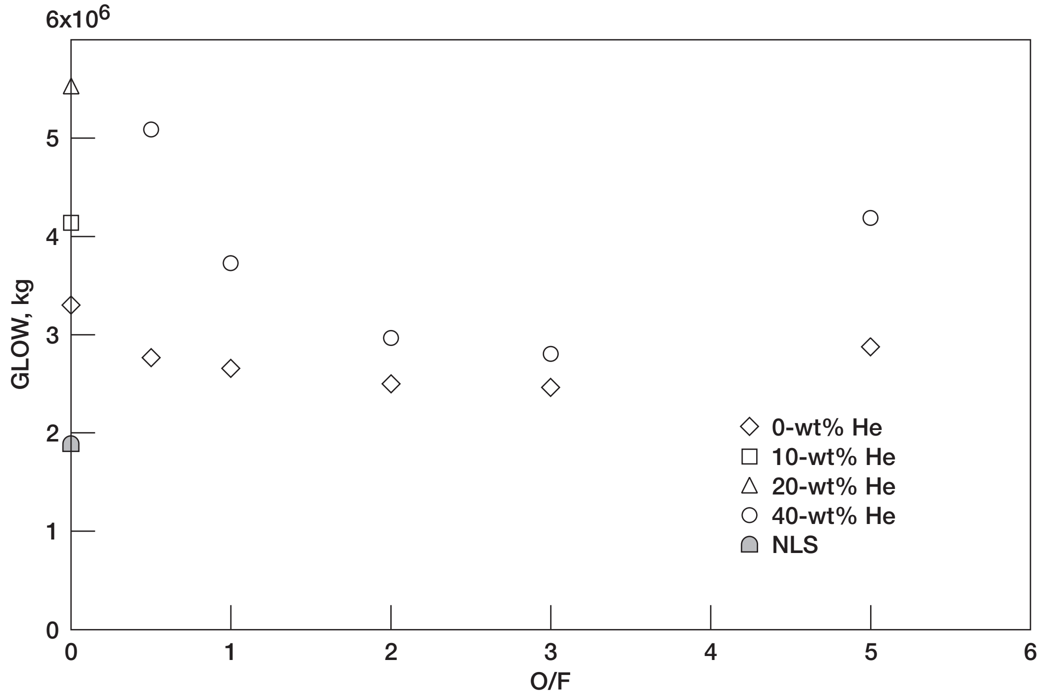

Figure 11.—Atomic carbon GLOW: 24–wt% C.

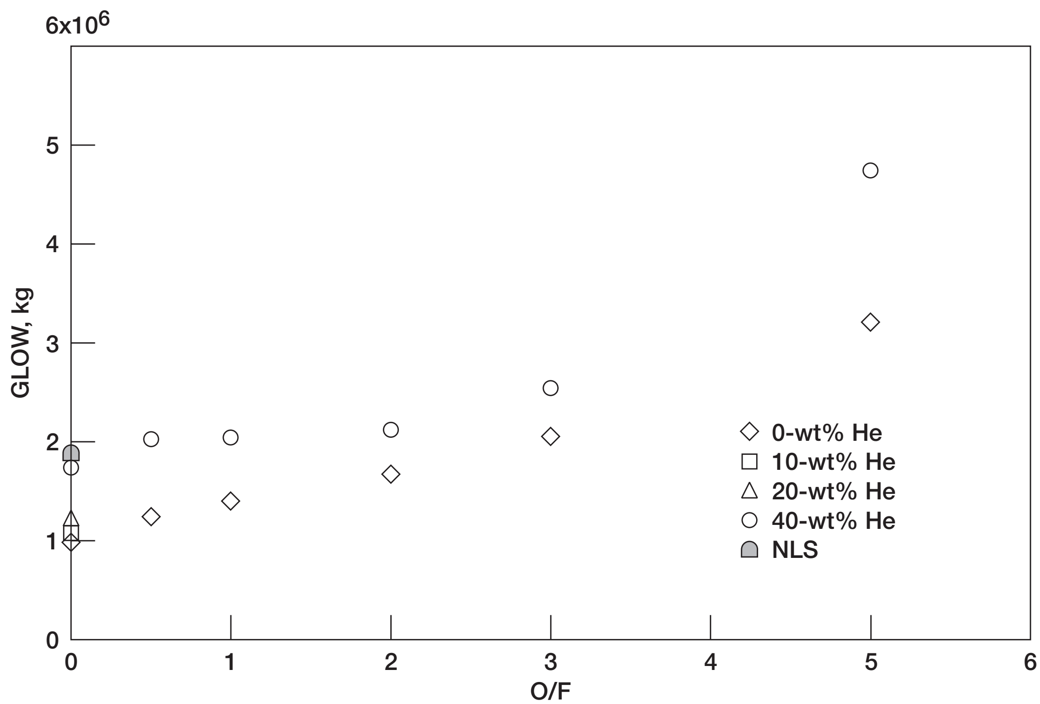

Figure 12.—Atomic carbon GLOW: 50–wt% C.

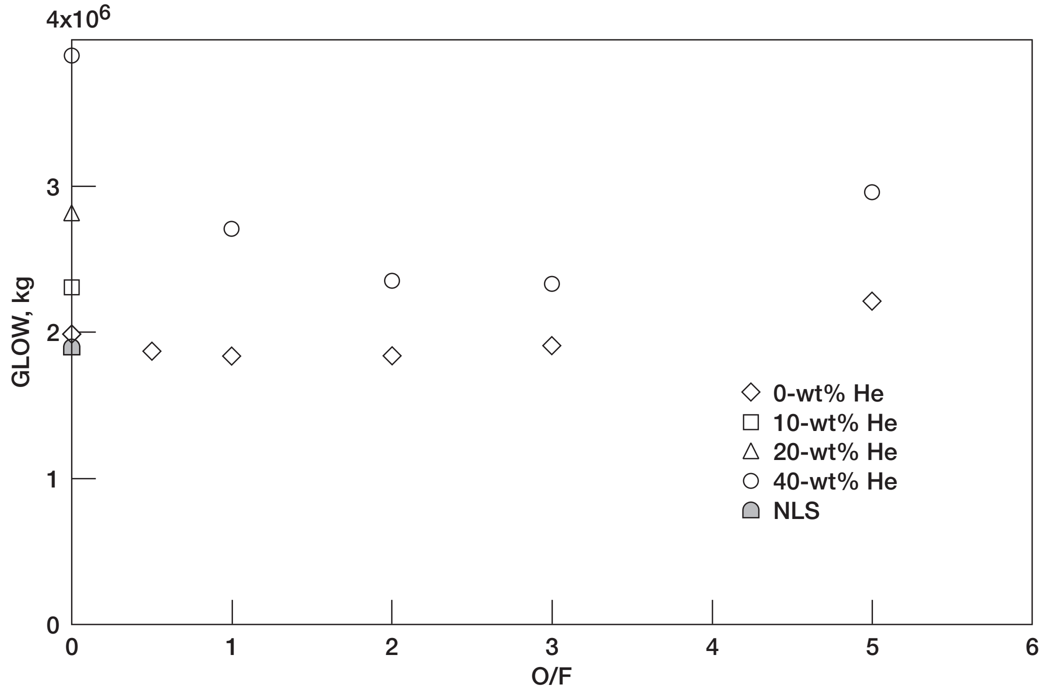

Figure 13.—Atomic hydrogen GLOW: 10–wt% H.

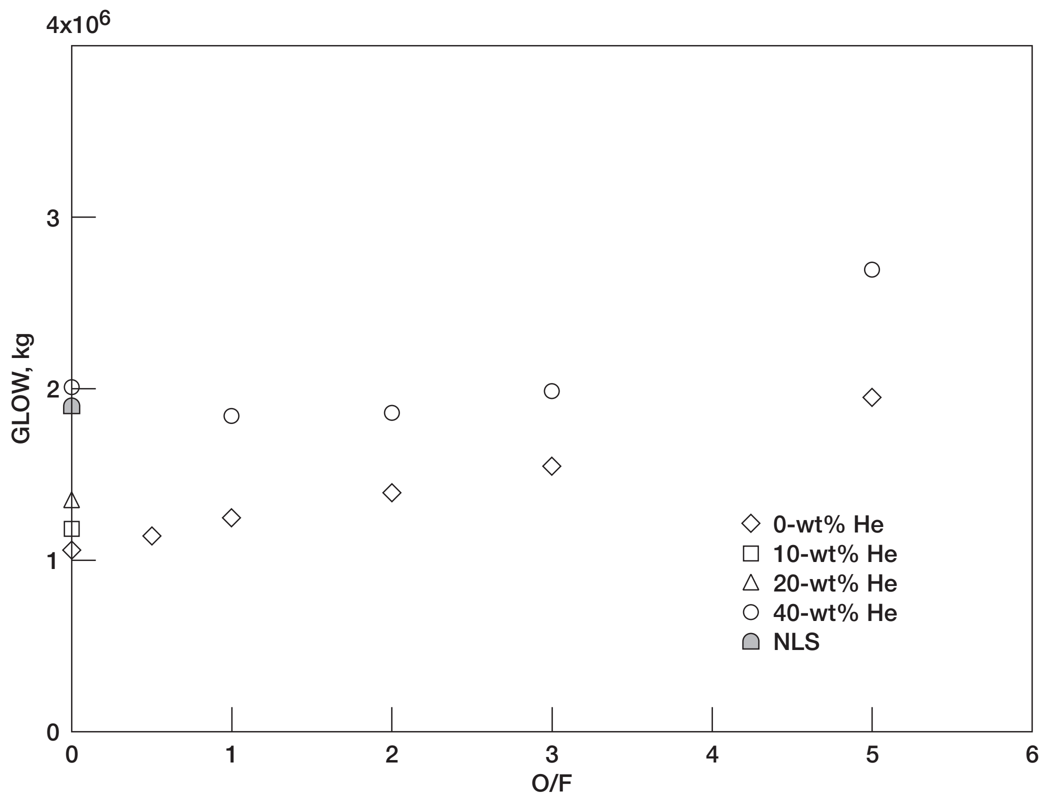

Figure 14.—Atomic hydrogen GLOW: 15–wt% H.

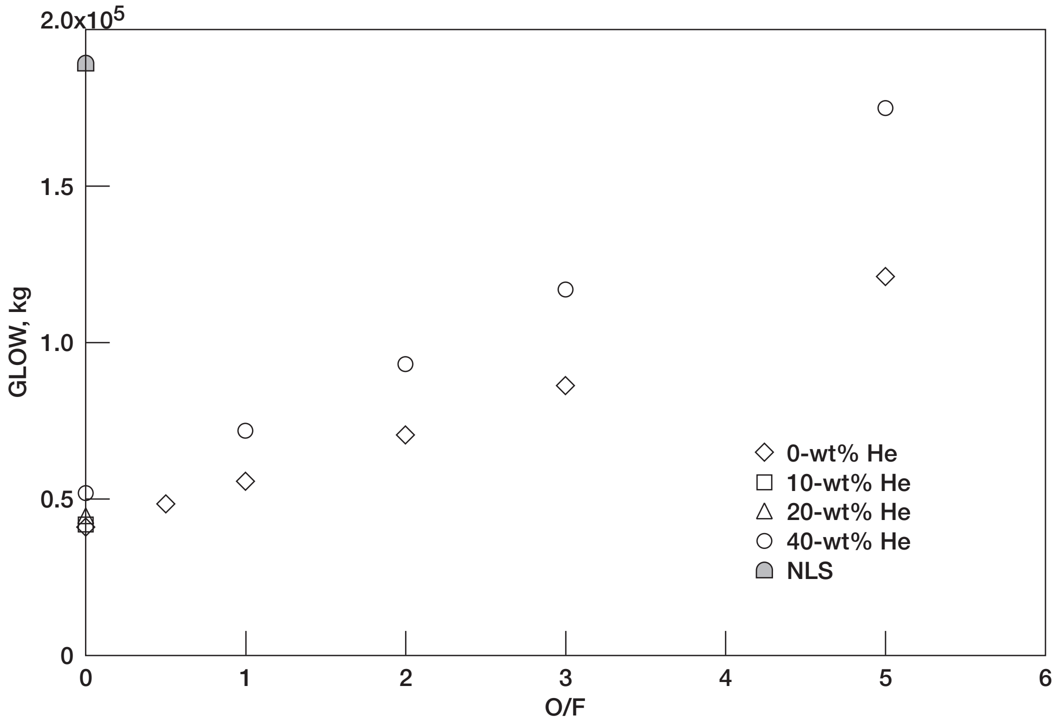

Figure 15.—Atomic hydrogen GLOW: 50–wt% H.

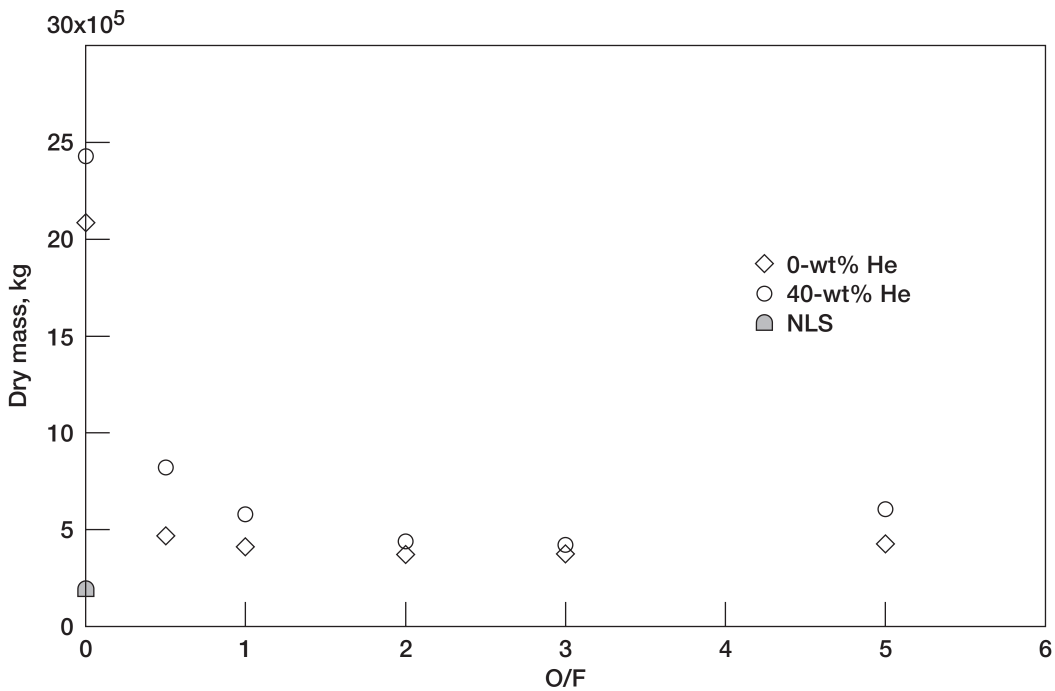

Figure 16.—Atomic boron dry mass: 22–wt% B.

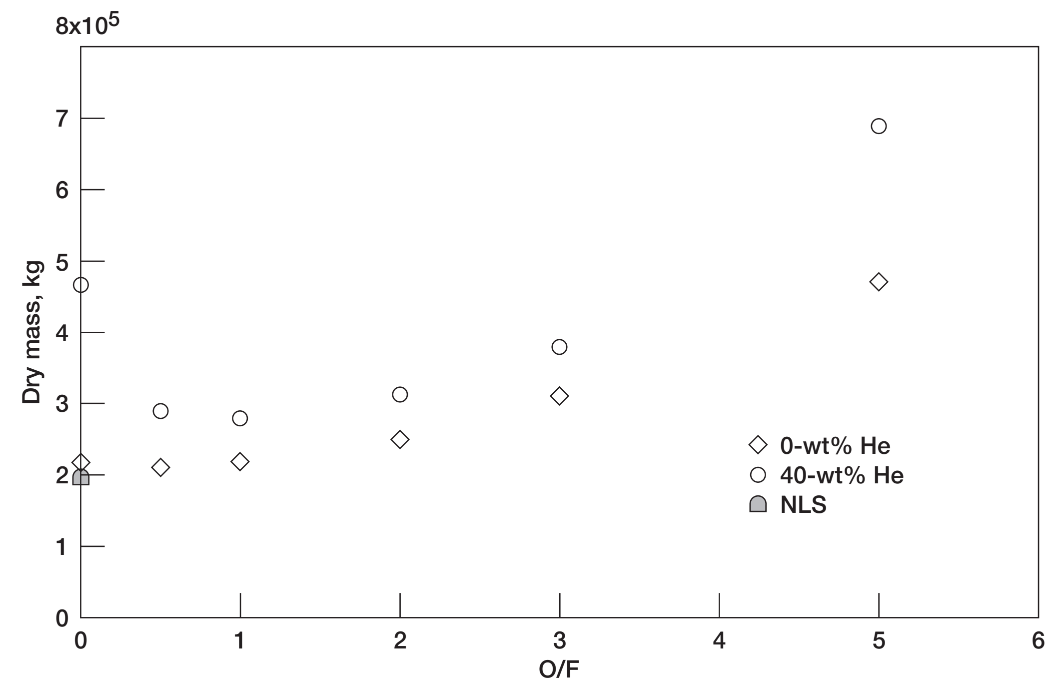

Figure 17.—Atomic boron dry mass: 50–wt% B.

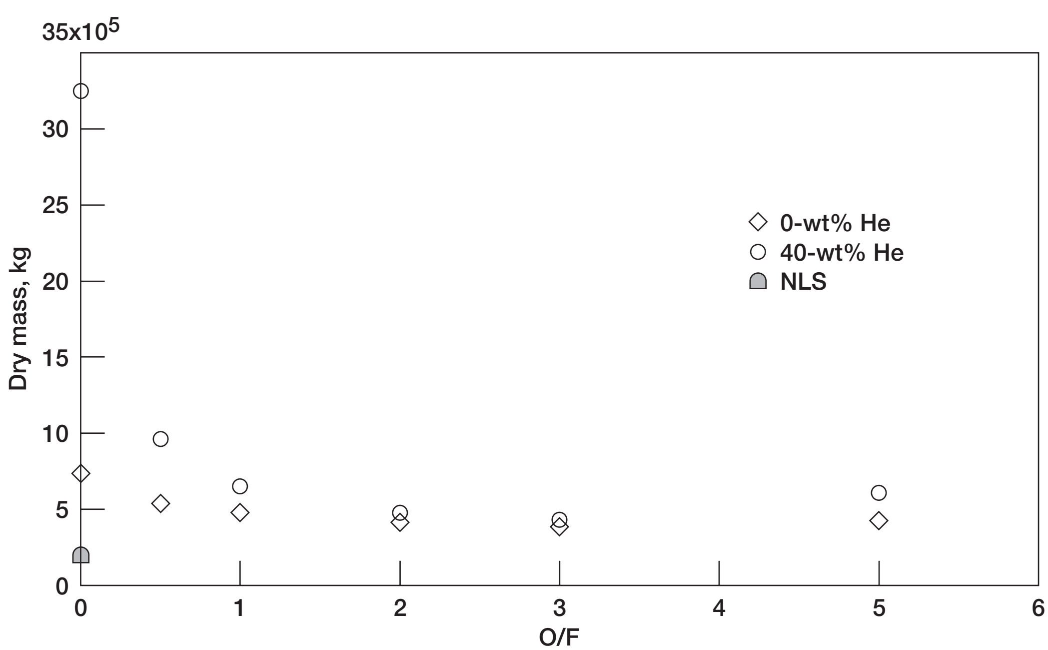

Figure 18.—Atomic carbon GLOW: 24–wt% C.

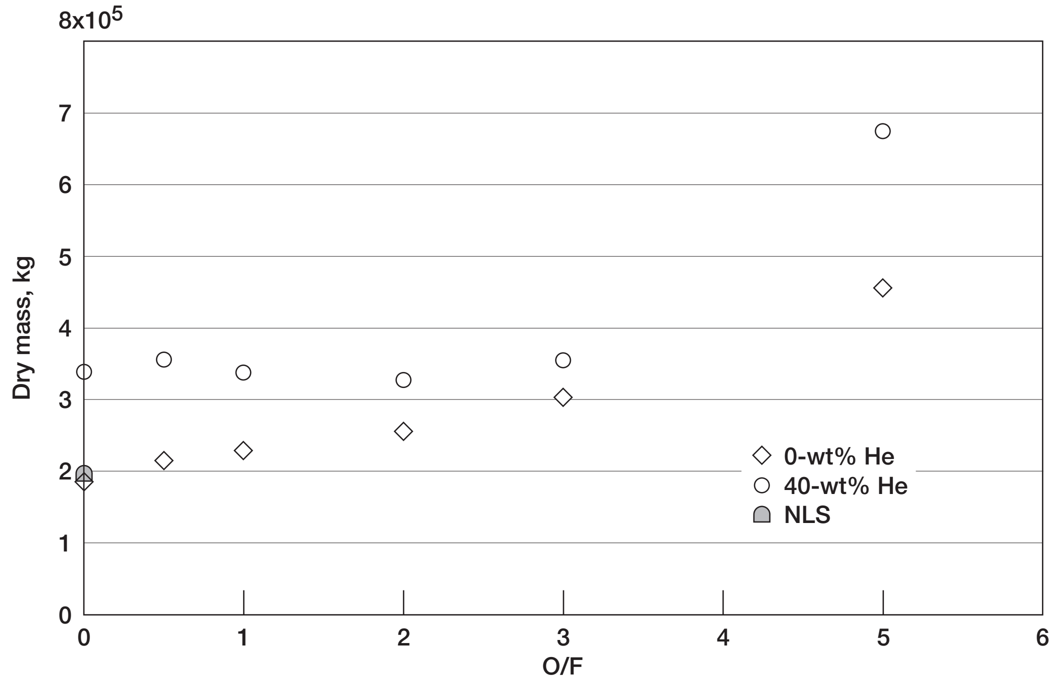

Figure 19.—Atomic carbon dry mass: 50–wt% C.

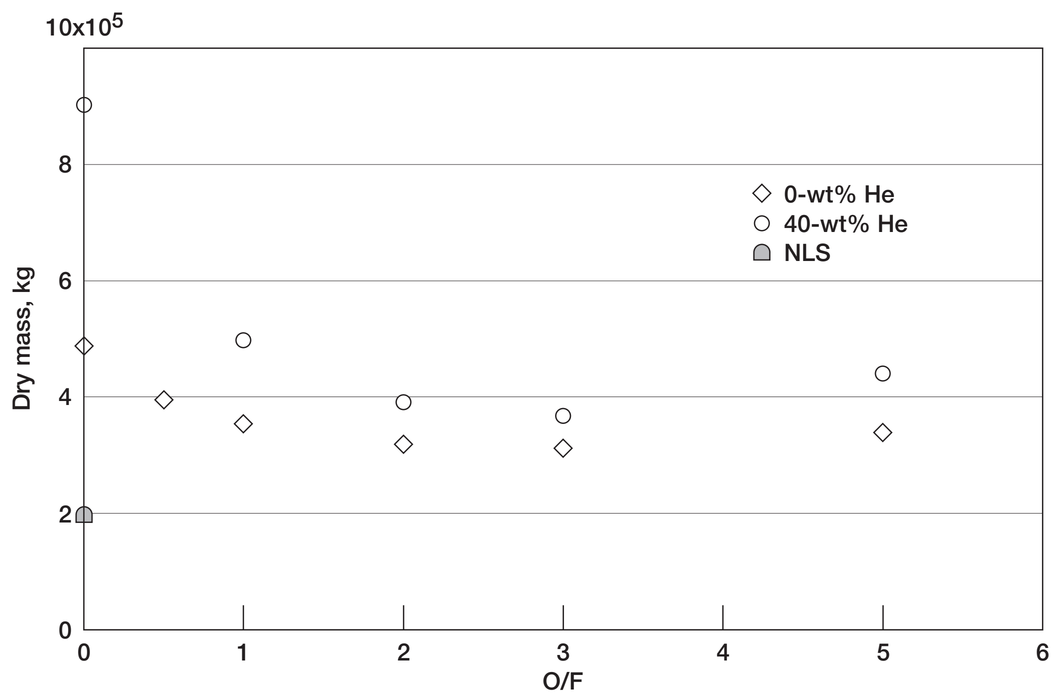

Figure 20.—Atomic hydrogen dry mass: 10–wt% H.

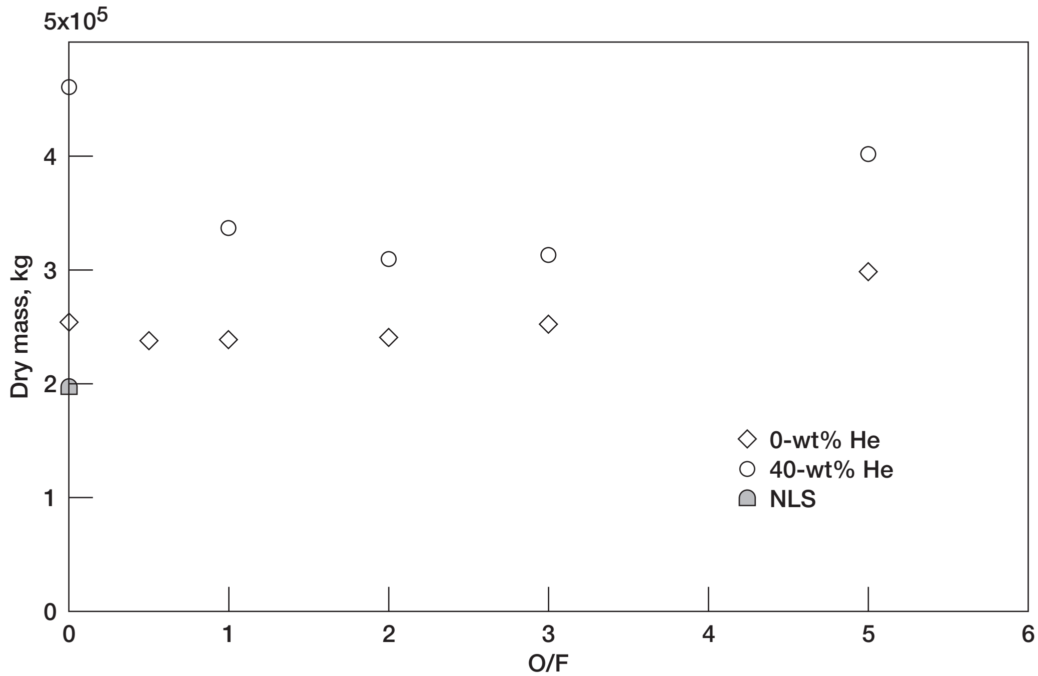

Figure 21.—Atomic hydrogen dry mass: 15–wt% H.

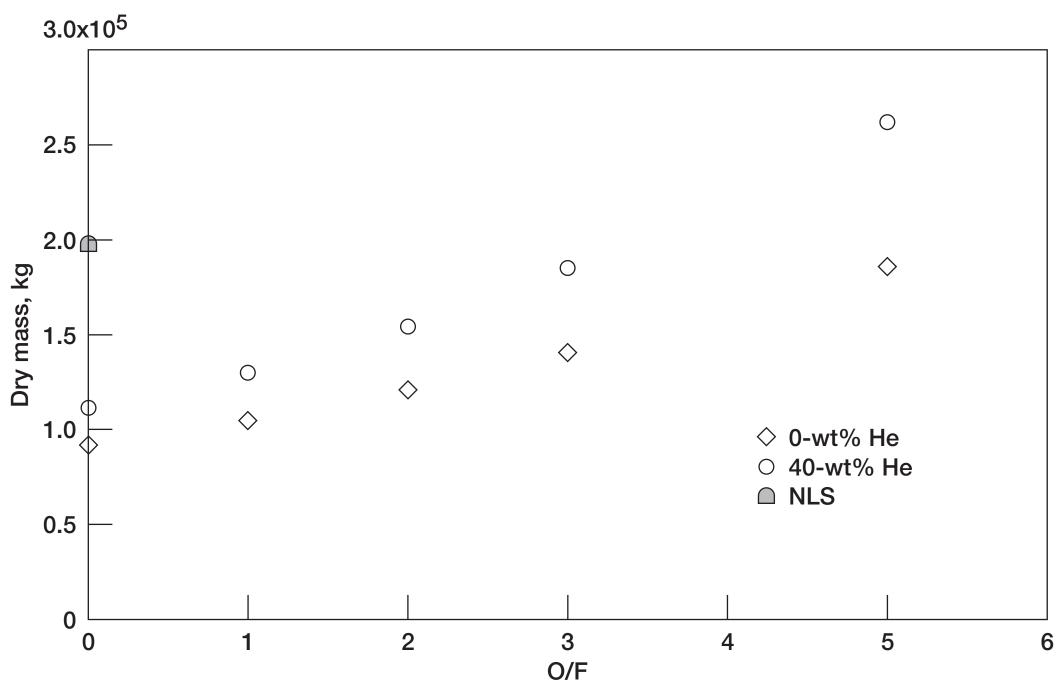

Figure 22.—Atomic hydrogen dry mass: 50–wt% H.

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11. SUPPLEMENTARY NOTES

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13. ABSTRACT *(Maximum 200 words)*

Atomic propellants for bipropellant launch vehicles using atomic boron, carbon, and hydrogen were analyzed. The gross liftoff weights (GLOW) and dry masses of the vehicles were estimated, and the “best” design points for atomic propellants were identified. Engine performance was estimated for a wide range of oxidizer to fuel (O/F) ratios, atom loadings in the solid hydrogen particles, and amounts of helium carrier fluid. Rocket vehicle GLOW was minimized by operating at an O/F ratio of 1.0 to 3.0 for the atomic boron and carbon cases. For the atomic hydrogen cases, a minimum GLOW occurred when using the fuel as a monopropellant (O/F = 0.0). The atomic vehicle dry masses are also presented, and these data exhibit minimum values at the same or similar O/F ratios as those for the vehicle GLOW. A technology assessment of atomic propellants has shown that atomic boron and carbon rocket analyses are considered to be much more near term options than the atomic hydrogen rockets. The technology for storing atomic boron and carbon has shown significant progress, while atomic hydrogen is not able to be stored at the high densities needed for effective propulsion. The GLOW and dry mass data can be used to estimate the cost of future vehicles and their atomic propellant production facilities. The lower the propellant's mass, the lower the overall investment for the specially manufactured atomic propellants.

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